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Fatigue Life Evaluation for Turbine Rotor Using Green's Function

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Abstract

Turbine rotors of fossil power plant are operated under the severe stresses resulted from high temperature and high pressure during start up. While steam temperatures through components abruptly change from low temperature and high temperature, thermal stresses reach the design limit at the same time and reduce the remaining life of rotor.
The purpose of this paper is to carry out fatigue analyses reflecting the results of the thermal stress simulation during start up and shutdown. The simple and quick simulation during turbine start up is developed with Green's Function. And temperature and stress transfer Green's functions applied to critical locations of rotor. Green's function is the thermal stress by the unit change of steam temperature. This method is useful of the thermal stress simulation at the start up. Therefore, it is anticipated that the proposed scheme adopting Green's function and operating histories can be utilized for remaining life time evaluation of turbine rotors.

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Keyword: Turbine rotor; Green's function; Thermal stress

1. Introduction

Increasing the aged fossil power plants over 20~30 years in Korea, it is imperative that the remaining life of them be closely evaluated and new technology are introduce in order to inform plant utilities to much information. Recently, operation condition of fossil power plants in Korea is changing from base load to weekly start up and shutdown. Critical components of fossil power plants are operated under temperature and pressure transients.

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Nomenclature

$E(p,t)$	temperature distribution of the body at zero temperature due to a unit step load
$\Phi(\tau)$	time varying boundary condition
$G(p,t)$	Green's function for the thermal stress at point p
τ , t	time
t_d	decay period
ν	Poisson ratio
N	number of cycle

An important characteristic of a steam power plant is its ability to allow for a sufficient number of start-ups and load changes without impairing the operation reliability and safety of the unit. Transient regimes arising during start-ups, shut-downs and load changes give rise to considerable thermal stress in heavy components of the high and intermediate pressure (HP/IP) turbines. Accurate knowledge of these thermal stresses induced in the components is thus required for the integrity and lifetime assessment of the unit. The rotor is the highest capital cost component in steam turbine and requires long outage for replacing the new one. It is known as general that start-up and shutdown operation greatly affect on steam turbine life. The start-up stress of rotor which is directly related life is composed of thermal and rotational stresses. The thermal stress is due to the variation of steam flow temperature and rotational stress is due to the rotation speed of itself.

In this paper, the analysis method of start-up stress of rotor which considers simultaneously temperature transition is proposed. The simple and quick simulation during turbine start up and shutdown is developed with Green's Function. And temperature and stress transfer Green's functions applied to critical locations of rotor. The fatigue analyses are carried out reflecting the results of the thermal stress simulation during start up. This method is useful of the remaining life time evaluation of turbine rotors.

2. Green's function method for thermal stress calculation

Green's function is defined as the response of a system to a standard step or impulse input. It contains all essential information of the system when it is properly defined. The transient temperature distribution subjected to time varying thermal boundary conditions can be expressed as:

$$T(p,t) = \int_0^t E(p,t-\tau)\frac{\partial}{\partial \tau}\Phi(\tau)\,d\tau \tag{1}$$

Under the quasi-static thermo elasticity, the thermal stress in an elastic body is a unique function of temperature. Based on Green's function concept and the Duhamel theorem, the thermal stress due to a small change in the boundary temperature at time t can be expressed from Eq. (2) as follows:

$$\sigma_T(p,t) = \int_0^t G(p,t-\tau)\frac{\partial}{\partial \tau}\Phi(\tau)\,d\tau \tag{2}$$

Physically, $G(p,t)$ represents the thermal stress distribution of the component, due to a unit step change at the boundary condition. Green's function $G(p,t)$ converges to a constant value after a "decay period" which is a function of the size of the body. Equation can be described as:

$$\sigma_T(p,t) = \int_{t-t_d}^{t} G(p,t-\tau)\frac{\partial}{\partial\tau}\Phi(\tau)\,d\tau$$

$$= G_s(p)\Phi(t) + \sum_{t-t_d}^{t}\widehat{G}(p,t-\tau)\Delta\Phi(\tau) \tag{3}$$

As we knew the thermal stress by the unit change of steam temperature, Green's function, thermal stress can be calculated from equation (3).

3. Green's functions for a turbine rotor

3.1. Stress analysis by Finite element method

A HP rotor is a very complex component, and modeling of such components is a difficult task. However, following the recent progress in computer and software, better knowledge if heat transfer coefficients and accurate experimental measurements of in-service temperatures, it becomes realistic to consider such calculations. To select the monitoring location for a critical point of the turbine rotor, detailed stress analyses are carried out for the thermal loads.

The thermal stress of turbine is determined with temperature variation and temperature variation rate. The temperature variation is getting higher in short time, increasing thermal stress. Figure 1 shows the thermal stress distribution of HP turbine rotor after cold start-up. The maximum stress of 473MPa occurs in the groove of the control stage at 60 minutes after power generation.

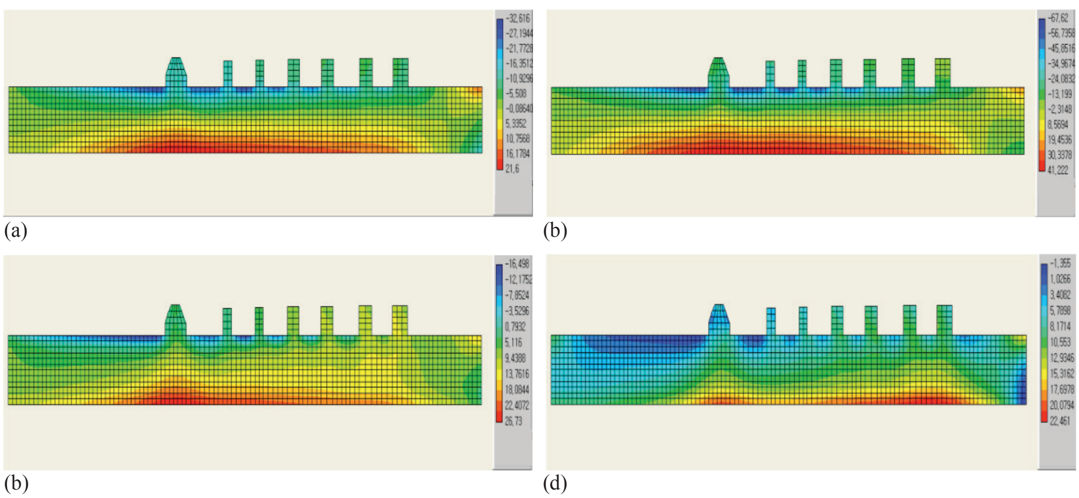

Fig. 1. Thermal stress distribution of HP turbine rotor (a) after 40 minutes power generation; (b) after 60 minutes power generation; (c) after 140 minutes power generation; (a) after 200 minutes power generation;

3.2. Green's functions

When there is a thermal load, the maximum stress occurs at the location of the groove of the control stage. This is mainly due to the thermal stress through the hoop direction. Therefore, we consider actual fatigue monitoring of the groove of the control stage.

When following the general Green's function method described in Section 2 above, a thermal stress analysis for a unit step change of the temperature time history is performed to calculate Green's functions at a monitoring point. In this analysis, the temperature is changed from preheat temperature of rotor by unit step load, which has a stress free condition. The material property data used for these analyses are listed in Table 1.The Green's functions at the monitoring point are calculated in Fig. 2. Among the Green's functions, the decay period for the numerical integration of Eq. (3) is determined to be 100 minutes from Fig.2.

Table 1. Material properties of CrMoV steel used in Green's function calculation

Properties(Unit)	Values
Density (kg/m^3)	7830
Heat coefficient (kJ/kg)	0.116
Conductivity (kJ/m s ℃)	5.83 X 10^{-3}
Modulus (MPa)	182021

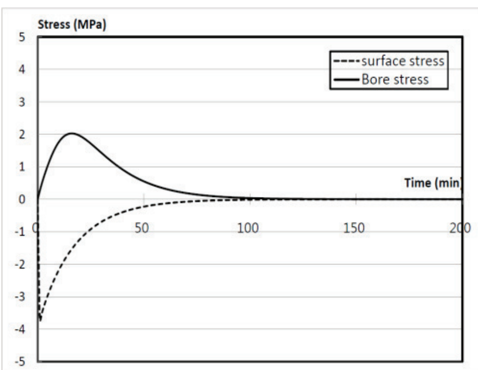

Fig. 2, Green's function

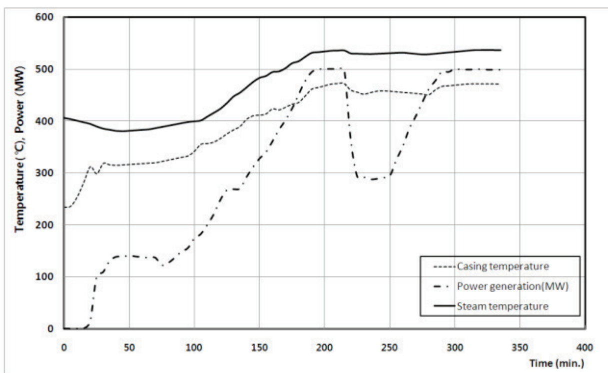

Fig.3. Cold start-up condition

3.3. Thermal stress calculation by Green's function

The thermal stress of turbine rotor is calculated by Green's function method during start up. Fig. 3 is the condition of the steam temperature and power generation. To verify the calculated Green's functions, the thermal stress time histories are calculated by FEM with constant material properties. Fig. 4 presents the comparison results between Green's function method and FEM. As shown in the figures, the thermal stress time histories by Green's function method show very good agreement with those by the detailed FEM. From these results, it is verified that the calculated Green's functions for the steady state and the transient are reliable, and the algorithm of Eq.(3) used in the calculation is applicable to a fatigue monitoring system due to its fast calculation time and accuracy.

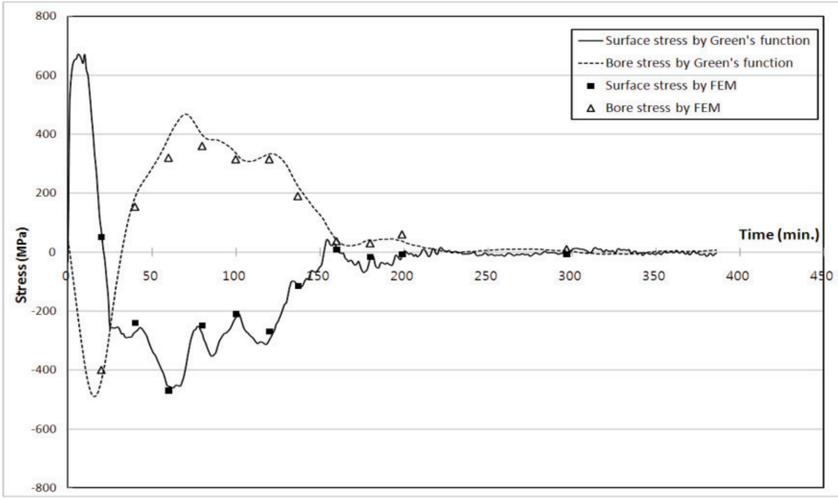

Fig.4. Comparison between Green's function method and FEM with start up schedule

4. Fatigue damage evaluation

The potential failure mechanism on the rotor surface is one of high temperature low cycle fatigue. Thus, the material strength depends not only on material itself, but also on the temperature level and on the loading frequency. The low cycle fatigue curve can be used for determining the expected life of high temperature turbine rotor. The curve used to specify turbine operating practices is shown in Fig. 5.

Fatigue damage calculation is defined as Miner's rule. In case that various kinds of stresses are applied to material, fatigue damages are accumulated independently. According to this assumption, Miner suggested the fatigue damage evaluation as the following:

$$\frac{N_1}{N_{f1}}+\frac{N_2}{N_{f2}}+\cdots+\frac{N_i}{N_{fi}}=\sum_{i=1}^{k}\frac{N_i}{N_{fi}} \tag{4}$$

$$D=\sum_{i=1}^{k}\frac{N_i}{N_{fi}} \tag{5}$$

Initially, the surface at the groove of control stage is subjected to tensile stress because of inflow of low temperature steam by rapidly opening control valve. After 25 minutes. The load condition is changed to compressive stress. Turbine rotor is damaged by the repetition of tensile and compressive stress during start up. The maximum tensile stress of 671 MPa occurs at the groove of control stage from Fig. 4. The maximum compressive stress is 460MPa. The total stress range during cold start up is 1131MPa.

To know the low cycle fatigue life, the total stress range should change to the total strain range. In the elastic condition, the total strain range can be described as:

$$\Delta\varepsilon=\Delta\sigma\times(1-\nu)/E \tag{6}$$

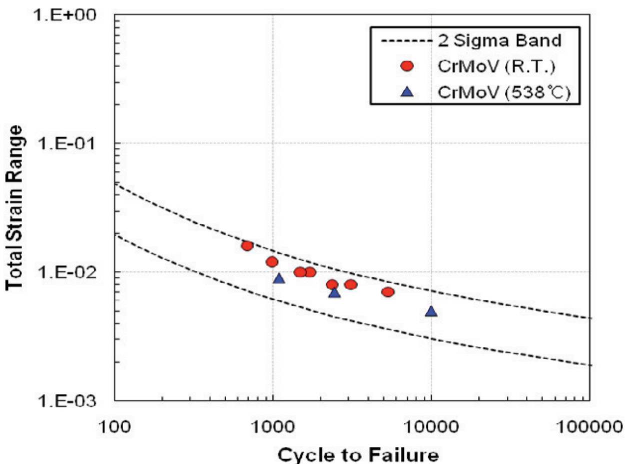

Fig.5. Low cycle fatigue curve for CrMoV steel

The total strain range is 0.00442 from Eq.(6). When the groove of control stage is occurred the total strange range of 0.00442, the expected start number of turbine rotor for cold start condition is 3500 cycles from Fig. 5. Turbine rotor is accumulated damage of 0.0286% per a cold start up.

5. Conclusions

The thermal stress analysis of turbine rotor is applied to Green's function method. Green's function method allows the indiscrete stress analysis at specific location such as the groove of the turbine rotor under transient thermal loading conditions. The thermal stresses by Green's function method correspond to those by the detailed FEM in the transient condition.

The fatigue damage is calculated by the results of the thermal stress simulation using the Green's function method. This method is useful of the fatigue life time evaluation of turbine rotors. Therefore, the fatigue damage of turbine rotor can be monitored by using the Green's function method in the real operating conditions of power plants.

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